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Blast Mitigation Using Water— A Status Report

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CONTENTS

1. Introduction	2
2. Definition of Terms	3
3. A Brief Review of the Literature	5
3.1. Past Usages of Water Barriers	5
3.2. Past Usage of Water Sprays	15
4. Methods of Blast Mitigation	30
5. Mechanisms of Blast Mitigation	31
6. Key Issues to be Resolved	35
7. A Plan of Action	37
8. Summary	38
9. Acknowledgments	38
10. References	39

Blast Mitigation using Water – A Status Report

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Abstract

The need to mitigate the effects of blast waves has been heightened by the recent incident with the USS Cole. In the spirit of one of the findings of the DoD USS Cole Commission, that there is a need for, “More responsive application of currently available military equipment, commercial technologies, and aggressive research and development,” this report reviews the current knowledge base on blast mitigation using water and identifies the key issues that need to be resolved in order to develop an effective water-based blast mitigation system for shipboard use in both peacetime and wartime.

There are several ways in which the use of water sprays can mitigate the effects of an explosion in a ship compartment. It may 1) break up larger droplets into finer mist (the breakup process extracts energy from the shock and weakens it); 2) directly lead to an attenuation of the shock waves produced; 3) reduce the intensity of secondary shock and pressure wave reflections from the walls and other objects in the enclosure; 4) slow down or quench the chemical reactions taking place behind the shock waves; and 5) dilute the concentration of explosive gases in the enclosure and hence prevent a secondary gas explosion or fire. In addition, the interaction depends on whether we are dealing with a

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shock wave, detonation or deflagration wave and the amount of water and size of the droplets that are present. Under certain circumstances the introduction of water spray could have an adverse effect by improving fuel-air mixing and accelerating flame propagation. These conditions have been identified in this report.

The ability of water mists to mitigate the effects of blast waves is unquestionable based on the evidence presented in this report. The unresolved issue is the effective mitigation that can be achieved in specific scenarios, such as in a shipboard explosion. This can be resolved only by considering relevant parameters, such as size of the enclosure, geometric complexity of the enclosure, amount of water available, time available to deploy the mist under different scenarios and the size and volume of mist that can be generated cost effectively in a timely manner.

1. Introduction

The attacks on Khobar Towers in June 1996 and, more recently on USS COLE (DDG 67), in the port of Aden, Yemen, on 12 October 2000, have visually demonstrated the extensive damage that can be inflicted on personnel and facilities by the detonation of commonly available explosives. There is a critical need to develop and demonstrate *anticipatory* damage control response system that will limit internal shipboard explosion damage. Ideally, such a system should have a dual utility, function as a fire suppression system for peacetime fires and as a blast mitigation system in combat or terrorist scenarios. A water-based system has the potential to fulfill this dual need and at the same time reduce life-cycle costs. The history, benefits and implementation of a water-mist fire suppression system for shipboard use have been extensively discussed and documented elsewhere (for example, Refs. 1-4) and hence will not be dealt with in this report. The focus of this report is on blast mitigation using water-based systems. The objective of this report is multifold. First, past work in the US and elsewhere, both military and civilian, that is publicly available is briefly reviewed. Then a critical assessment of our current scientific understanding of the problem is presented. This highlights the voids in our current knowledge base. Finally, a plan of action to fill some of the voids is proposed. In

order to make the problem tractable with limited resources, the focus of the proposed research is on a specific Navy scenario.

An incoming missile is detected and a water-mist system has been activated near the area likely to be hit. Will the mist system sufficiently weaken the peak-overpressure from the exploding warhead ? If not, or if the mist could not be turned on early enough, will it dampen the quasi-steady pressure and any secondary effects of the missile hit such as gas explosions and deflagrations so that the damaged area can be limited? The focus of this investigation is to identify key parameters that will ensure a positive response to the above questions.

2. Definition of Terms

While going over the papers and other publications from a variety of international sources, some academic but others industrial and governmental, it is found that many terms, such as blast, explosion and detonation are loosely used and sometimes mean the same thing! This clouds the interpretation of the results. Since it will be time consuming and probably contentious to arrive at a consensus definition of the terms involved, the terminology adopted for the purposes of this report is presented here. While a number of sources have been consulted, these are primarily based on the guidelines provided by the Center for Chemical Process Safety of the American Institute of Chemical Engineers (AIChE) [5].

A **Blast** is defined as “a transient change in the gas density, pressure, and velocity of the air surrounding an explosion point.” [5]. The change can be either discontinuous or gradual. A discontinuous change is referred to as a shock wave while a less abrupt change is usually referred to as just a “pressure wave”. The key point is that when people refer to “blast waves”, they do not necessarily mean “shock waves.”

A **detonation** is defined as “a propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic

velocity in the unreacted material.” When the reaction front advances at less than the sonic velocity, we have a **deflagration**. In both detonations and deflagrations, the reaction front is moving into an essentially premixed fuel-oxidizer mixture. In many scenarios, detonations and deflagrations do not occur due to the absence of a well-mixed fuel-oxidizer mixture.

An **explosion** is a release of energy that causes a blast. That is, an explosion and detonation are not synonymous and an explosion may not even involve a shock wave. This is an important point because many papers that deal with water-mist suppression of an explosion do not address some issues that are crucial to the mitigation of the shock damage from an explosive.

An **impulse** is a measure that is used to quantify the damage caused by a blast wave. It is calculated by the integration of the pressure-time history curve.

The **flame speed** is the speed of a flame burning through a flammable mixture, measured relative to a fixed observer. The **burning velocity** is the velocity measured relative to the unburned gases immediately ahead of the flame. That is, the flame speed is the sum of the burning and translational velocities of the unburned gases. It can be quite high and can in some cases be dominated by the fluid velocities. Only the planar, laminar burning velocity is a fundamental property of a premixed combustible mixture.

A **vapor cloud explosion** is an “explosion resulting from the ignition of a cloud of flammable vapor, gas, mist” [5] in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure.

In addition to the above terminology, it is worthwhile to recall the definitions of two terms that are frequently used in the description of water mists and sprays. The **Sauter mean diameter** is defined as the diameter of a spherical droplet whose surface area to volume ratio is the same as the ratio of the sum totals of the surface areas and

volumes of all the droplets in the sample. The **Water volume fraction** is the fraction of any given volume in the spray envelope that is occupied by the liquid water.

3. A Brief Review of the Literature

In the case of a confined explosion, water has the potential to mitigate the shock pressure as well as the gas pressure loading developed inside a confining structure. There are two broad areas of past research. One is the usage of bulk water as passive barriers to mitigate the effects of blast waves. This is analogous to and essentially a replacement for conventional barriers made of concrete or sand. Typically these barriers are placed close to or around explosives, such as in a magazine, or in special containment vessels for the destruction of unwanted munitions. The second area is the direct application of water sprays or mists to an area that may have combustible material. This is analogous to the use of water sprays for fire suppression. However, the primary aim here is to prevent ignition by reducing the concentration of a combustible vapor to below its flammability limits. When it is not possible to prevent ignition, then water sprays may reduce the severity of vapor cloud explosions and subsequent gas over pressures. Primary application of this technique has been in offshore oil platforms and coalmines. A study of the past work in these two areas is useful in formulating a plan to tackle the Navy problem described earlier.

3.1 Past Usages of Water Barriers

One of the techniques of mitigating the damage from blast waves from explosives is the erection of water-barriers of different types. Sometimes this approach is also described as a “passive” approach because typically the kinetic energy of the explosion is what is used to break the containers and disperse the water. Such methods have been traditionally used in coal mines where tubs or troughs filled with water are placed so that the blast wave tips or shatters the container [6-10]. Other examples of the application of this concept range from protecting embassies and other civilian facilities (using it as an

alternative to concrete barriers) to reducing the hazard around ammunition storage and disposal sites.

The major national and international organizations conducting these tests have been:

USA

US Bureau of Mines, Pittsburgh, PA

Naval Civil Engineering Laboratory (NCEL) tests at the former David Taylor Research Center, MD (currently, NSWC-Carderock Division)

US Army Corps of Engineers (USACE), Huntsville, AL

Naval Facilities Engineering Service Center (NFESC), Port Hueneme, CA

Battelle Memorial Institute, Columbus, OH

SWEDEN

Defence Research Establishment (FOA) at Marsta, Alvdalen and Grindsjon

NETHERLANDS

TNO-Prins Maurits Laboratory, Riswijk

FRANCE

Groupe SNPE

UK

Ministry of Defense/ CESO(N), Bath

NORWAY

Christian Michelsen Institute, Bergen

Norwegian Institute of Technology, Trondheim

First, the key tests carried out by or for these organizations are summarized and then further details are provided, where available.

US Bureau of Mines

The initial emphasis of the work at the Bureau of Mines in the 1970's was on the suppression of coal dust explosions by the use of passive water barriers that tip over when impacted by a blast wave [6, 7]. Later on in the 1980s, experiments were conducted with both passive barriers such as bags that shatter and triggered barriers that spray water based on a sensor reading [8, 9]. Passive barriers tested included a long, flexible bag suspended from the roof of the mine and a rigid PVC trough. Both could hold up to 80 liters of water. The explosions were considered to be suppressed if the flames failed to propagate 30 m beyond the barrier. Both barriers were found to be effective under this definition. Other countries also seem to have tried a similar approach for mitigating explosions in mines [10]. The triggered or active system is discussed later when the effect of sprays on explosions is discussed.

NCEL Tests

These tests were conducted in 1990 at the former David Taylor Research Center (currently, NSWC-Carderock Division) to aid the Naval Civil Engineering Laboratory (NCEL) in the development of a High Performance (HP) magazine and have been referred to as NCEL tests [11]. The HP magazine is a multi-cell, earth-covered, reinforced concrete, box-shaped structure with a tunnel entrance. Ordnance is stored in cells that are designed to prevent any sympathetic detonation from ordnance stored in adjacent cells. In these tests, a cylindrical charge of 4.67 lb (2.12 kg) of TNT was exploded inside a closed chamber. In some of these tests, the explosive was "surrounded" by a three-wall cubicle with water-filled walls as shown in Fig. 1. In the presence of water, both the average gas pressure inside the chamber and the impulse were reduced by as much as 89%. A typical gas pressure plot comparing the results with and without water is shown in Fig. 2.

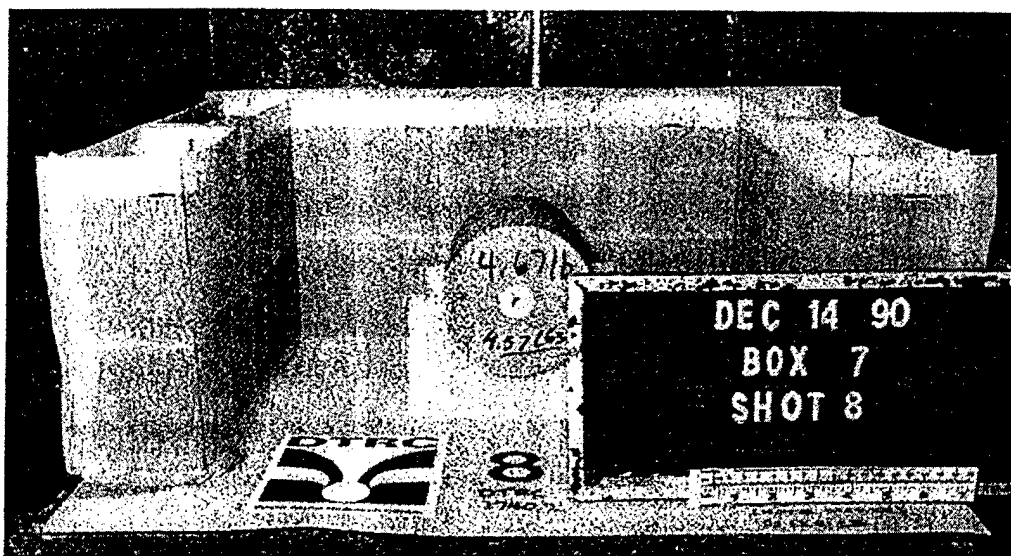


Fig. 1 NCEL test setup showing the three water-filled walls and the cylindrical explosive.

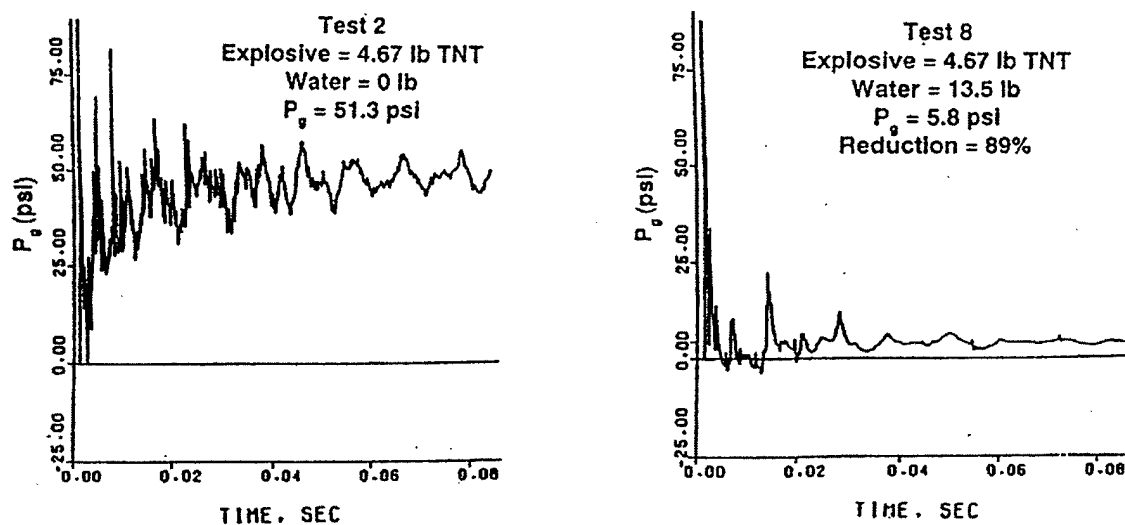


Fig2. Time history of the gas pressure from the detonation of 4.67 lb (2.12 kg) of TNT measured inside a test chamber without any mitigation (Test 2) and with three water-filled walls (Test 8). The mean gas pressure is reduced by about 89 %.

USACE Huntsville Tests

The US Army Corps of Engineers (USACE) tested a munitions demolition container for unexploded ordnance disposal [12]. Water bags were placed around the explosive (within the container) to try to mitigate the effects of an explosion. A 70 % reduction of the gas pressure from 350 psi (0.246 kg/mm^2) to 100 psi (0.07 kg/mm^2) was obtained for a 4-lb (1.81 kg) charge of TNT.

NFESC Work

In FY97, NFESC began looking at water mitigation concepts for application in confined (Missile Test Cells, Underground Magazines) and partially confined (e.g. earth-covered magazines) facilities. They have reported [13] only on a limited number of tests that were conducted at the Aberdeen Test Center. In these tests, the water-to-explosive ratio was varied from 2:1 to 4:1. For low charge densities, they conclude that a ratio of 2:1 is sufficient for effective suppression. Tests with venting show that bulk water is effective even in such cases. Another aspect of their work appears to be sponsoring an evaluation study [13] of existing numerical tools in conjunction with the Singapore Department of Defense. The results from this evaluation study appear to be inconclusive while highlighting the need to address the combustion of oxygen-deficient explosives. Their overall conclusion is that water is effective in reducing the internal gas pressures even in the presence of venting.

Battelle Work

The Battelle Memorial Institute in Columbus, OH has developed a proprietary blast suppression system [14]. Their primary focus is on mitigating the effects of a large vehicle bomb (LVB), placed in an open environment. Each unit has nozzles configured to disperse water into the air surrounding the bomb. Preferably, the transmission occurs before the explosion of the bomb and continues after the explosion as well. Each unit has an adjustable flow rate, an adjustable flow pattern, and an adjustable droplet size. Because of the proprietary nature of their device, many details have not been presented. However, their work is one of the few that recognizes the potential importance of parameters such as droplet size and flow pattern. Many researchers in this area of work

quite often view water as a bulk medium that somehow absorbs the impact of the explosion.

Early Swedish Tests

One of the earliest (1974) reported studies on the effects of water on mitigating blast waves is that of Ericsson [15]. In an open test site, 50 gm TNT charges were surrounded by 2 times, 5 times and 10 times their weight of water and exploded. The charge was placed inside a balloon completely surrounded by water. The pressure was measured 0.7 m from the charges and the peak pressure was reduced by approximately 5-20% compared with bare charges.

Large-Scale Swedish Tests

Unexpected results from a full-scale test by FOA in the KLOTZ Club Tunnel [16] in Alvdalen, Sweden, have generated much interest and discussion. The large-scale facility at Alvdalen is quite complex, including two crossing tunnels with a chamber at the end of each and a single tunnel entrance with a berm just outside to provide absorption and deflection of fragments. A schematic is shown in Fig. 3.

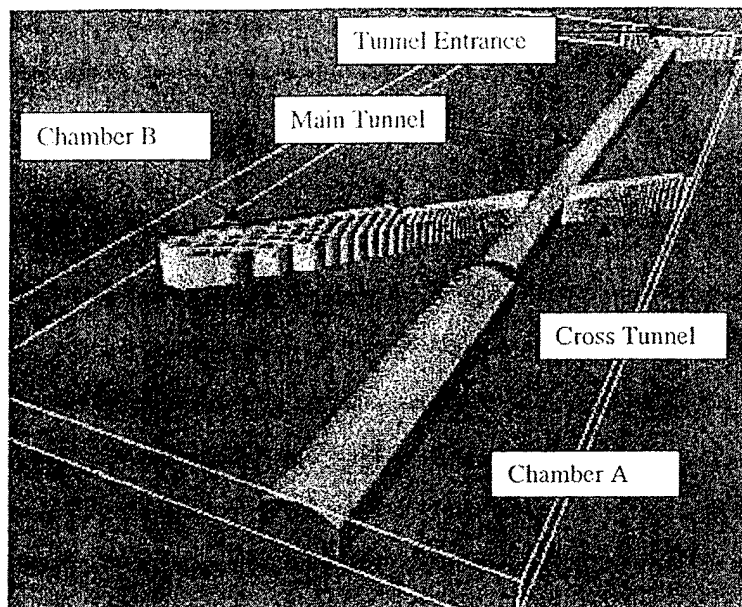


Fig. 3 A Schematic of the large-scale Alvdalen tunnel.

In the original tests conducted in 1989, without water, 180 six-inch artillery shells (with a TNT equivalence of about 1000 kg) were detonated simultaneously inside the large chamber (A) with the 60-m long tunnel. In 1996, the tests were repeated with water barrels (containing 2000 kg of water) placed close to the charge. The controversial result was the observation that although some reduction in the peak pressure was observed inside the tunnel, there was actually some increase observed outside, near the entrance to the tunnel. Although the increase was only modest, the overall negative result on the effectiveness of water as a mitigation agent has raised concerns. The complex geometry involved (as shown in Fig. 3, there is a connecting cross-tunnel with an additional chamber), the roughness of the walls, the casings around the artillery shells used in the tests, the design of the berm at the tunnel entrance, and the scale of the test have all been speculated as possible reasons for the observed results.

Small-Scale Swedish Tests

In these tests, a 1/20-scale model of one of the KLOTZ Club Tunnels, discussed above was used [17]. The explosion chamber was a tube with cross-section of 0.030 m^2 , 1.25 m long and was connected to a 3.75-m long steel pipe with a cross-section of 0.0144 m^2 . Here, 200 gm of High Explosive (HE) was placed in the explosion chamber and was surrounded by 400-600 gm of water in plastic cups (this corresponds to 1600 kg HE and 3200-4800 kg water in the full scale). Pressure reductions in excess of 50% were obtained if water was placed in contact with the charge. If the water was separated, the reduction could be as low as 10%.

Medium-Scale Swedish Tests

In these medium scale tests by FOA-Marsta [18] shock tubes were used: tube 3 (4.4 m^2 cross-section) with charges up to 100 kg HE and tube 4 (1.8 m^2 cross-section) with 1-5 kg HE were surrounded with water bags and barrels in the range 1-25 kg. Significant attenuation is reported.

Small-Scale Tests of Joachim and Lunderman

The geometry consisted of a simplified version of the tunnel with a chamber connected to a duct [19]. The chamber volume was 0.365 m^3 , the duct area was 0.017 m^2 and its length was 4.0 m. Charge densities in the range 1.67 to 5 kg/m^3 were tested with water/explosive ratios from 0.67 to 3.3. These small scale tests report lowering of the pressure in the chamber by about 70% with water completely surrounding the charge. They note that in this configuration, there is an upper limit for effective amount of suppression that can be attained and increasing the amount of water beyond that gives only a marginal improvement. FOA conducted similar tests in 1997 [20] to investigate the effect of steel casings (used in the artillery round tests at Alvdalen) but found no significant effect.

TNO-PML, Netherlands Tests

Small-scale tests were conducted at TNO-PML in 1995 and 1996 [21]. The 1995 tests were conducted in a bunker, 2 m in diameter and 2.45 m in height. Using 1-kg of a plastic explosive (PETN, 7 mm dia x 14 cm length) in this enclosure results in a loading density of 0.13 kg/m^3 . The explosive was placed on the floor of the bunker at the center of the enclosure. Keeping the doors of the bunker closed during the tests, results in a build up of the detonation gasses within the enclosure. The nearly constant gas pressure observed in the enclosure is referred to as quasi-static pressures (QSP). The maximum value observed for the QSP during a number of trials using bare charges was noted to be about 130 kPa. This is useful as a reference value to assess the effectiveness of various mitigation strategies in this enclosure. Key observations from these tests are: 1) a reduction from 130 kPa to about 15 kPa was obtained (85% reduction in pressure) 2) more effective reduction of the QSP is found when an air gap is created between the explosive and the water, 3) larger reduction is obtained for higher water/charge ratio, 4) the explosive should be fully enclosed by the water for maximum effect but significant reduction (50 %) in QSP was observed even when the water is not in the vicinity of the charge. The air gap was created by enclosing the explosive in an inner plastic box and filling the outer plastic box with water.

Test in 1996 dealt with bomblets placed in cylindrical containers with water or sand bags on top. These attenuators are devices to be placed over small ordnance items, like bomblets and mines, and should be able to capture most of the fragments and vent the blast away from demining personnel, in case the item accidentally explodes. Their tests showed that water was as effective as sandbags, both reduced the pressure by about 80%. Camera-recordings showed the generation of a sand or water jet, up to 30 m high in the air.

SNPE, French Tests

Both small-scale [22] and larger-scale tests [23] have been conducted by SNPE. In the small-scale tests at the CAPTIEUX test center, 0.1 kg of a “plastrite” explosive (87% PETN) was used. When the water surrounds the explosive, a key parameter was the ratio of the weight of water to the weight of the explosive. In this case, the scaled impulse ($\text{MPa}\cdot\text{ms}/\text{kg}^{1/3}$) drops when the ratio is increased from 0 to 5 and then remains constant. They recognized the difficulty of enclosing the explosive with water in practical situations, especially since they were evaluating water as an alternate to barricades made of soil, sand or concrete. Therefore, they erected a wall of water confined by PMMA sheets. They give nomographs of excess pressure (overpressure) as a function of wall thickness, charge/wall distance and charge/measurement location. They conclude that a water wall is a practical option.

As a follow on to the above tests, they also conducted larger-scale tests. Here the aim was to verify the previous observations using full-scale tests and also to conduct numerical studies. The explosive used was IREMITE 4000, which has a TNT equivalence of about 1 kg, for every 100 kg of the explosive. They specifically focused on the “Shadow area”, a region behind the wall that is approximately 4 times the height of the wall. Three tests were carried out: 1) a reference case with no water, 2) with 360 kg water barrier—bottles of water (10 cm thick) held with wire mesh (which also helps cut the bottles) in rows of shelves, and 3) a strong wall made up of six 2.5 tonne concrete blocks. They observed almost identical mitigation for both water and concrete. Mitigation

effects were mainly noticed in sensors placed less than 30 m from the explosive. They observed some positive impulse at 25 m for the concrete case and speculated that the wave just goes around the wall for this case.

Their modeling work used the MULTIMA 2D developed by AEROSPATIALE-Matra-Lanceurs. It “covers the same fields as standard Lagrangian or ALE codes such as LS-DYNA and AUTODYN” [23]. A second-order Godunov scheme is used to solve the convective transport equations. The shocked states are obtained using a Riemann solver and the behavior of the materials involved is characterized using a JWL equation of state. Various interface reconstitution algorithms are used to process mixed cells, that is cells made up of several materials. Their model does not take into account the break up of the water into droplets and the energy associated with this change. They also neglect thermal transfer between the fireball, hot gases and the water. Some qualitative results are shown that do not predict the positive impulse observed at longer distances.

MOD, UK Work

An empirical investigation of water as a blast suppressant was conducted for the MODUK/CESO(N), Bath, UK [24]. A test charge of 8.5 kg of PE4, equivalent to 10 kg of TNT, was detonated tamped by plastic water bags (6 tonnes) shaped as a cube. Blast shock suppression of 95 % was achieved but there was too much local disruption (enhanced cratering, enhanced ground shock and slugs of water flying out the faces of the cube). Then, instead of the cubical arrangement, a half-cylinder arrangement for the water bags was tried. The water dispersed as droplets but the cratering and ground shock were still as bad. Blast over-pressure suppression was still at 95 %. A special arrangement of bags reduced the cratering and ground shock but also reduced the suppression to 93 %. He notes that the conventional way to reduce cratering and ground shock is to place the charge off the ground. This was tested with a sphere of water. Cratering disappeared and no slugs of water were observed. Blast suppression was further reduced to 89 %. The comparative UK costs are: 9000 £ for water, 75,000 £ for concrete, and 100,000 £ for Steel. Since both steel and concrete can suppress the shock

100 %, he concludes that **nearly 90 % shock suppression can be achieved with water for roughly 9 % of the cost of steel or 12 % of the cost of reinforced concrete.**

Norwegian Research on Detonation Quenching

Quenching of detonations in acetylene-air and ethylene-air mixtures using a layer of water has been studied in Norway [25, 26]. The experimental set-up consisted of an 8 m long square tube with an internal dimension of 125 mm. A tube bundle consisting of 36 square tubes with an internal dimension of 17 mm was mounted inside the large tube. Tests were performed with and without a 2-mm layer of water in the bottom of each tube. Three different tube bundle lengths, 0.3, 0.5 and 1.0 m, were used. The tube bundle, even without the water is able to decouple the shock wave from the reaction front. Under certain conditions, the flame could transition back to a detonation outside the tube bundle. With a layer of water in the tube, the flame could be extinguished in most of the cases, thus preventing a detonation re-initiation. In such cases, the pressure is reduced to less than 4 bars and the velocity of the shock front is reduced to less than 750 m/s downstream of the tube bundle. One-dimensional simulations of these experiments carried out using the Random Choice method are not very encouraging [26].

From the brief summary provided above, it is clear that significant reduction (50-90%) in the peak-pressures and QSP can be obtained by surrounding an explosive with water or placing water in the vicinity of an explosive, at least in small-scale and medium-scale facilities. The amount of suppression does depend on the amount of water (up to a certain ratio) but more importantly the details of the actual placement of the water around the explosive significantly affects the amount of suppression attained.

3.2. Past Usage of Water sprays

Water sprays have been used extensively to suppress fires of various kinds. A natural extension of these applications has been to mitigate the effects of dust explosions, hydrocarbon mist explosions, and gaseous explosions. As defined earlier, the term,

“explosion” is used here in the broader context and does not imply the occurrence of detonations or the presence of shock waves.

A particular hazard of coal mines is that coal dust dispersed throughout the atmosphere may explode when subjected to an ignition source. Flame speeds in such explosions may reach several hundreds of m/s and the flow generated from such high-speed flame propagation may entrain additional dust allowing the explosion to propagate significant distances. In general, two means of coping with such events using water have been tried. A “passive” barrier system is similar to the usage of bulk water around explosives described earlier in that the high dynamic pressures generated in these explosions are used to rupture containers of water. In an active or triggered system, some precursor of the explosion event is used to trigger a water dispenser system that typically sprays water onto the path of the propagating flame. It is conjectured that the high flow velocities generated by the fast flames fragment the coarse sprays into finer droplets and it is these finer droplets that provide an effective mitigation [27].

Numerous organizations have been involved in this type of work, most notably, US Bureau of Mines, British Gas plc. and the University of Wales in the U.K., Norwegian Institute of Technology and Christian Michelsen Research Institute in Norway. The incident at the Piper Alpha platform in July 1988 appears to have renewed interest on the mitigation of explosions in offshore installations. That incident also illustrated that an accident can escalate rapidly from a relatively small initial release of gas to a series of explosions and fires and a major catastrophe involving the collapse of the offshore platform.

Early Research on use of Water Sprays

In a paper published in 1954, Gerstein et al. [28] indicated that they were successful in using water sprays in quenching detonations and in preventing transition to detonation in natural gas-air mixtures at initial pressures of 0.2-0.4 atm. The experiments were performed in a 93 m long horizontal shock tube of 61 cm internal diameter with two water sprays spaced approximately 1.5 m apart and 50 m from the ignition point.

Although the detonation wave was quenched, some sort of a disturbance continued to propagate down the tube.

Carlson et al. [29] demonstrated that water sprays were effective in mitigating both deflagrations and detonations in hydrogen-air mixtures in a tube 12 m long and 41 cm diameter. They used droplets that were nominally 500 microns in mean droplet diameter. Initial pressures were between 0.5 and 2 atm and the mixture concentration ranged between 4-28 % hydrogen in air. Detonations were rapidly attenuated by water sprays--both the pressures generated and the propagation speeds were reduced considerably.

Watts [30] showed that water sprays were effective in lowering the concentration of an ethylene cloud, initially contained in an 8 m³ polythene container to below the lower flammability limit. However, they found that it was possible to ignite the mixture before the lower limit was reached and a detonation could be initiated if a larger quantity (by a factor of three) of high explosive was used. Vincent and Howard [31, 32] showed that spraying water (mean droplet diameter of about 300 microns) into a developing hydrocarbon mist prevented the concentration from rising above the lower flammability limit and hence prevented an explosion.

The observations of Zalosh and Bajpai [33] were also at variance with that of Carlson et al. [29] since they found only a marginal modification in the lower flammability limit of hydrogen-air by water sprays. They found that the water densities required to suppress ignition were strongly dependent on droplet size and increased by an order of magnitude as the mean droplet diameter increased from 20 microns to 100 microns. This study highlighted the need to look at very fine water sprays or mists.

US Bureau of Mines

In the 1970s and 1980s, the US Bureau of mines conducted various tests to evaluate the ability of water to mitigate explosions in coal mines [34, 35]. Small-scale experiments on quenching flames and inerting methane-air mixtures were conducted by

Sapko et al. [34] using a 1m long vertical tube that was 15 cm in internal diameter. The combustible mixture was introduced through the tube's base and the inerting water or steam was introduced through another nozzle. For the inerting tests, they determined the water concentrations required to prevent incipient ignitions from becoming propagating flames. For the quenching tests, an upward propagating flame was met by a falling spray and the quenching limits were defined as the amount of water that extinguished a propagating flame. The amount of water needed for quenching was found to be much larger than for suppressing an incipient ignition in the same mixture. Heated sprays were found to be more effective. Another finding of their work was that water-droplets less than 10 microns in diameter were as effective as water vapor for inerting the mixture.

In another work at the Bureau of Mines, Ng et al. [35] explored the use of both actively triggered and passive water-barrier systems. The passive systems are similar to those discussed earlier where troughs or bags of water are used on the path of the blast wave. The triggered system tested was a 33 cm diameter spherical dispenser filled up to 70% with water and pressurized using nitrogen. When an event is detected, water was sprayed through spiral nozzles. They were able to suppress fully developed gaseous as well as dust explosions. They conjectured that the explosion may have fragmented the coarse water spray into finer droplets and thus improved their mitigating capacity.

Work of British Gas plc.

In a work at the Midlands Research Station of British Gas [36], experiments were carried out to investigate the ability of water sprays to limit flame speeds and overpressures produced in gas cloud explosions. They focused on water sprays because their previous work showed that a passive system involving bulk water was ineffective in reducing significantly the flame speeds and overpressures associated with flames propagating at high speeds through congested pipe work - a scenario of particular interest to them. However, they had found [37] that activation of water sprays before ignition is a potential way of mitigating the effects of explosions. In that work, a natural gas flame, traveling at over 500 m/s through repeated obstacles, was decelerated by a water spray

curtain to a low speed, which only generated low overpressures. Based on these encouraging results further research was undertaken.

Initial experiments with nozzles used in offshore water deluge systems were performed in an enclosure with a confined region up to 15 m in length. The rest of the enclosure was an open region formed by a steel framework covered with transparent polythene sheet to contain the flammable mixture prior to ignition by a spark. A schematic of the test setup is shown in Fig. 4 (taken from Ref. 32). Four tests with natural gas or propane were carried out. The first test, without suppressants, showed high-speed flames traveling in natural gas at an average speed of about 500 m/s and generating overpressure peaks of greater than 10 bar. In test 2, with propane-air, transition to detonation occurred approximately 15 m from the spark, resulting in speeds of about 1800 m/s and peak overpressures of over 30 bar. Water sprays produced by an open pendant type nozzle, located only in the initial confined region, reduced speeds in natural gas (test 3) and prevented detonation of a propane-air mixture (test 4). The overpressures produced were 0.35 and 1.7 bar, respectively. The reduction in flame velocity obtained in one of the tests is shown in Fig. 5.

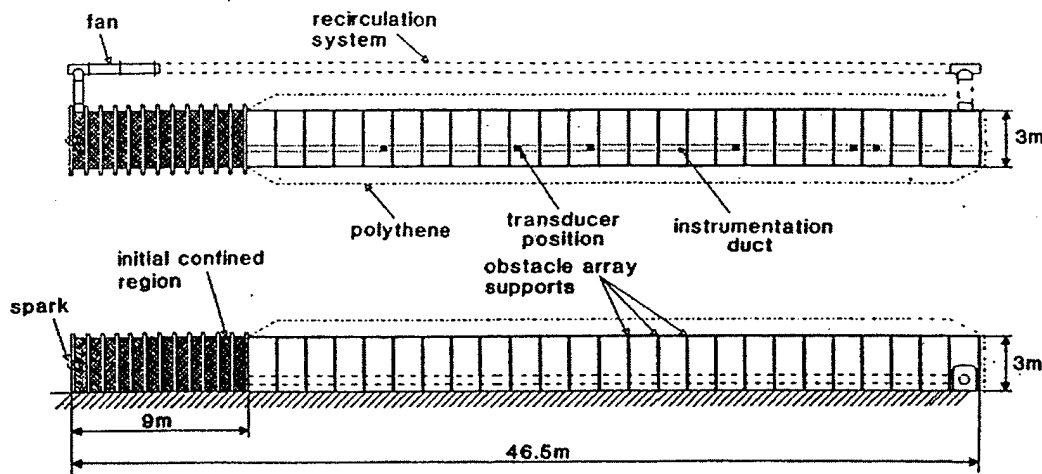


Fig. 4 A schematic of the test rig used to study the effect of water sprays on gas explosions.

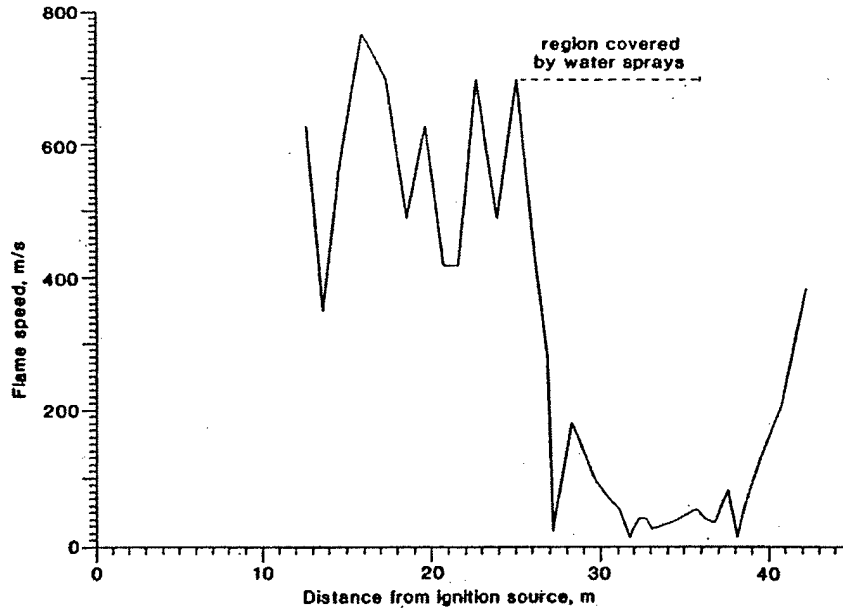


Fig. 5 Flame speed as a function of distance demonstrating the rapid deceleration of a high-speed deflagration in a natural-gas/air mixture by the application of water sprays.

Experiments in configurations representative of an offshore module were also conducted. Chamber size was 4-m by 10-m by 2.1-m high with two solid walls and a solid roof. The other two walls were polyethylene sheets. Obstacles used were steel girders and pipe work with a mean blockage of approximately 10 %, typical of offshore modules. Nozzles (36 of them) were mounted in a 4 x 9 matrix at 1-m x 1-m spacing, approximately 0.25 m below the roof. Nozzles used were the 90-degree cone type, operating at approximately 3-bar water pressure. The flow rate through each nozzle was approximately 12 liters/minute. Droplet diameter was about 430 microns. Figure 6 (taken from Ref. 32) shows mitigation from 780 mbar to about 180 mbar but also shows that the peak occurs earlier (200 to 240 ms after ignition) compared to 300 ms for the unmitigated case. They attribute this shift in the occurrence of the peak to an initial acceleration of the flame by spray-induced turbulence.

One of the concerns raised by the above work was the effect of the scale of the experiments [38]. It was not clear if small-scale experiments were representative of the

hazard presented by a fire or explosion resulting from a larger, more realistic gas release. They suggest conducting larger-scale experiments and using validated models for further studies. In further tests, a large-scale facility at Spadeadam (UK) that is 182 m³ in volume (9 m x 4.5 m x 4.5 m) was used. Using proprietary nozzles, overpressures were mitigated (see Fig. 7, taken from Ref. 34) when the 4.5 m square face of the chamber opposite the ignition point was completely open. However, when the area of the vent opening was reduced to one ninth of the cross-sectional area of the chamber, there was no mitigation and actually there was a slight increase. They explain that the effect might be because of the large droplets involved which were not capable of extracting enough heat energy from the flame during the time-scale of the explosion to provide mitigation. The small increase might be due to the turbulence generated by the spray. In the vented case, greater flame acceleration would break up the droplets into smaller size and provide improved mitigation. This work suggests the use of smaller droplets directly for effective mitigation.

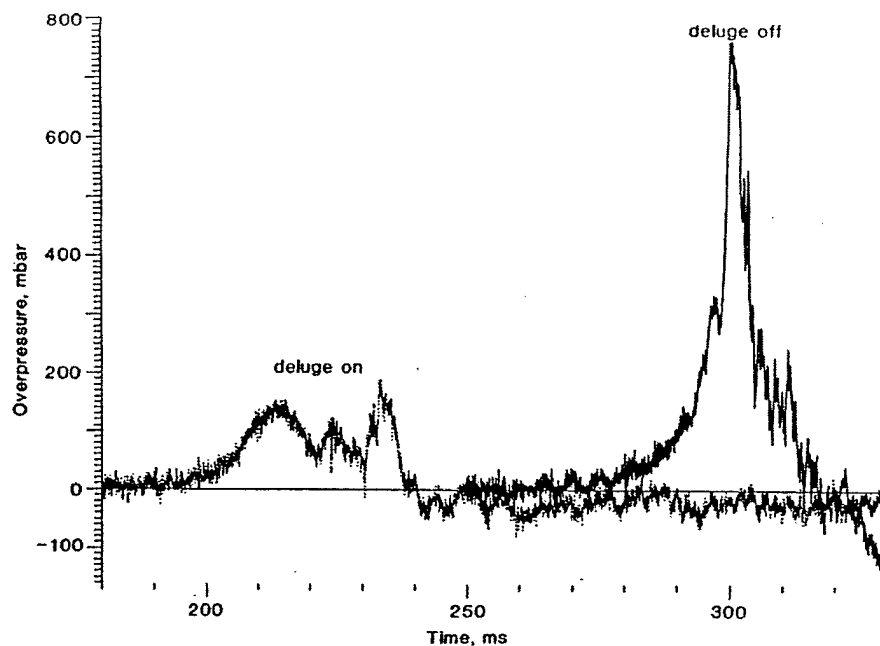


Fig. 6 Comparison of time history of overpressures recorded at the same transducer for equivalent tests with and without water deluge. Notice the shift in the occurrence of the peak overpressure with the application of the water spray. The volume of the rectangular test chamber was 84 m³.

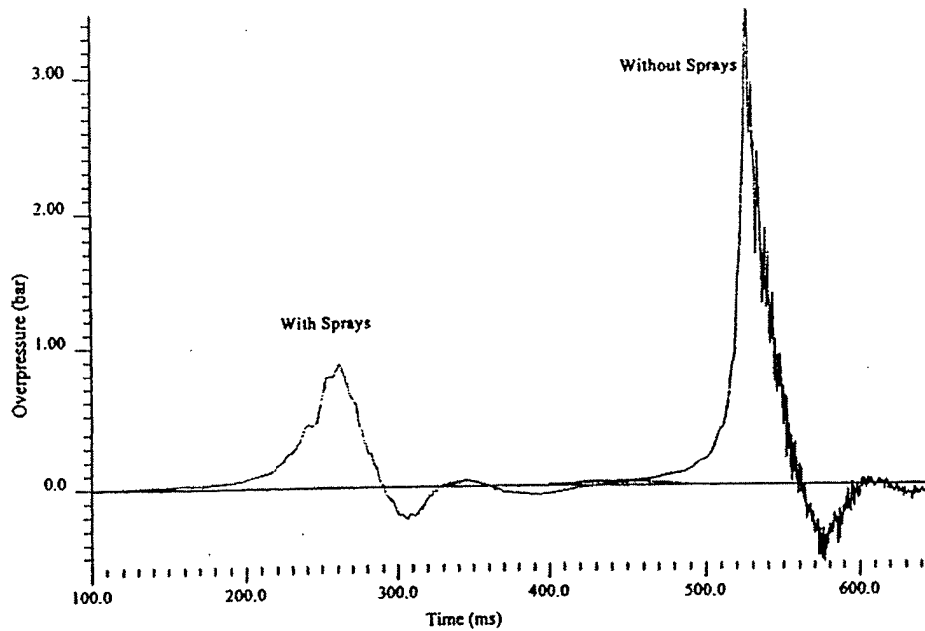


Fig. 7 The effect of water deluge on overpressures in the large-scale Spadeadam facility (182 m³.) Notice the differences in the magnitude of the overpressures.

Again, we observe in Fig. 7 that the peak over-pressure occurs earlier with water spray than without any water. Comparing Figs. 6 and 7, we get a general idea of the dependence of the actual magnitude of the over-pressure on the scale of the experiments. Note that the scale of the experiments depends both on the amount of explosives used as well as the actual volume of the test chambers. We also notice that in both cases the water sprays are effective in reducing the over pressures by a factor of 3 to 4.

The results from twenty-three tests conducted at the 182 m³ Spadeadam facility are discussed by Catlin et al [39]. They make several general statements based on their past experiences such as: a) “for water spray mitigation to be effective the water must be distributed in a uniform way throughout the whole module and hence general area deluge is mandatory”, and b) sprays may be less effective in “confined geometries” in which the flow speeds are relatively low and droplet breakup less probable. Then they report on the effect of parameters such as flow velocities from different nozzles, nozzle drive pressure, the nozzle separation distance and the addition of foaming agents to the supply water. Higher nozzle pressures will give rise to more turbulence whilst also producing smaller

droplets; reduced nozzle spacing would increase the water droplet density; and foaming agents reduce the surface tension, thus increasing the likelihood of droplet breakup.

In all ten tests with a highly confined geometry in which there is a small vent on one side of the chamber, water sprays increased the peak overpressures within the chamber and brought forward the time of occurrence of the peak relative to the values measured in the base cases. The addition of a foaming agent caused marginal reduction in the internal overpressures. For the thirteen tests with the vented side left completely open, the internal overpressures were significantly less than those in the base cases. In most cases, the external overpressures were reduced by an even larger factor, which they attribute to high flame acceleration. Note that in this configuration, there is pipe work congestion that results in high flame speeds. The mitigation effect was found to increase for larger numbers of obstacles, higher nozzle supply pressures and larger number of nozzles. Both the nozzles used produced similar sized droplets whose diameters were largely between 600-800 microns. They also state that increasing the water pressure has the effect of reducing the mean droplet size in inverse proportion to the square root of the nozzle supply pressure.

The overall conclusion from their work is that “a mitigative effect will only occur if the flame accelerations are sufficiently high.” Under high confinement the sprays did not provide any substantial mitigating effect and the number of obstacles, the type of nozzle or water pressure used made little difference to the overpressure generated. Therefore, there is a need to investigate “mechanisms for producing sprays with much smaller droplets as a way of mitigating against unacceptable overpressures in highly confined geometries” [39].

Work at the University of Wales, Aberystwyth, UK

Extensive investigations have been carried out at the Center for Explosion Studies of the University of Wales on the use of water sprays for mitigating the effects of both deflagrations and detonations [40-46]. Many of the earlier studies have been summarized

in a review paper by Jones and Thomas [44] and the more recent work in a paper by Thomas [46].

An important observation from this group is that sprays are quite proficient at suppressing detonations and that the initial droplet size distribution is a very important parameter. Vertical shock tubes were used with the driven section filled with acetylene, hydrogen or ethane-air mixtures. Suppression of detonations was achieved and appeared to improve as the droplet size became finer [40]. The droplet sizes were between 200 and 1000 microns. It was suggested that the high-speed flow behind a detonation wave was able to fragment water droplets by "a process of continuously stripping mass from their surfaces." The mass stripped in this way formed exceedingly fine droplets that were more easily vaporizable and better heat sinks than their parent droplets.

Thomas et al. [42] and Jones and Thomas [43] also conducted detailed studies of the effects of sprays on flames propagating through shock tubes. Two experimental configurations were used. In one configuration, the tube was 5 m long and had an internal diameter of 76 mm giving a length-to-diameter (L/D) ratio of about 66. The other configuration was a shorter tube of length 0.5 m and a L/D ratio of 2. The results were geometry dependent. In the short tube ($L/D=2$), the spray enhanced explosions but in the longer and larger tube there was mitigation (pressure reduction by a factor of 2 to 3). Several mechanisms of flow-droplet interactions were discussed but a definite explanation for these observations has not been made. The enhancement in the short tube was attributed to spray-generated turbulence.

Another issue highlighted by the work of this group is the difficulty in characterizing the effective droplet sizes used in experiments. A typical spray size distribution taken from the work of Brenton and Thomas [45] is shown in Fig. 8. Data from two commercial techniques for droplet size measurements: a MALVERN particle size analyzer and a DANTEC PDA are also shown in the Figure. The size parameter plotted is D_{32} , which is the ratio of droplet volume to surface area. From the Figure, we observe that caution must be exercised in comparing the droplet size effects quoted in

different papers because the measurement techniques used could result in significantly different size estimates. The figure also highlights the difficulty in characterizing a spray using a single parameter such as a mean droplet diameter, measured at a single location.

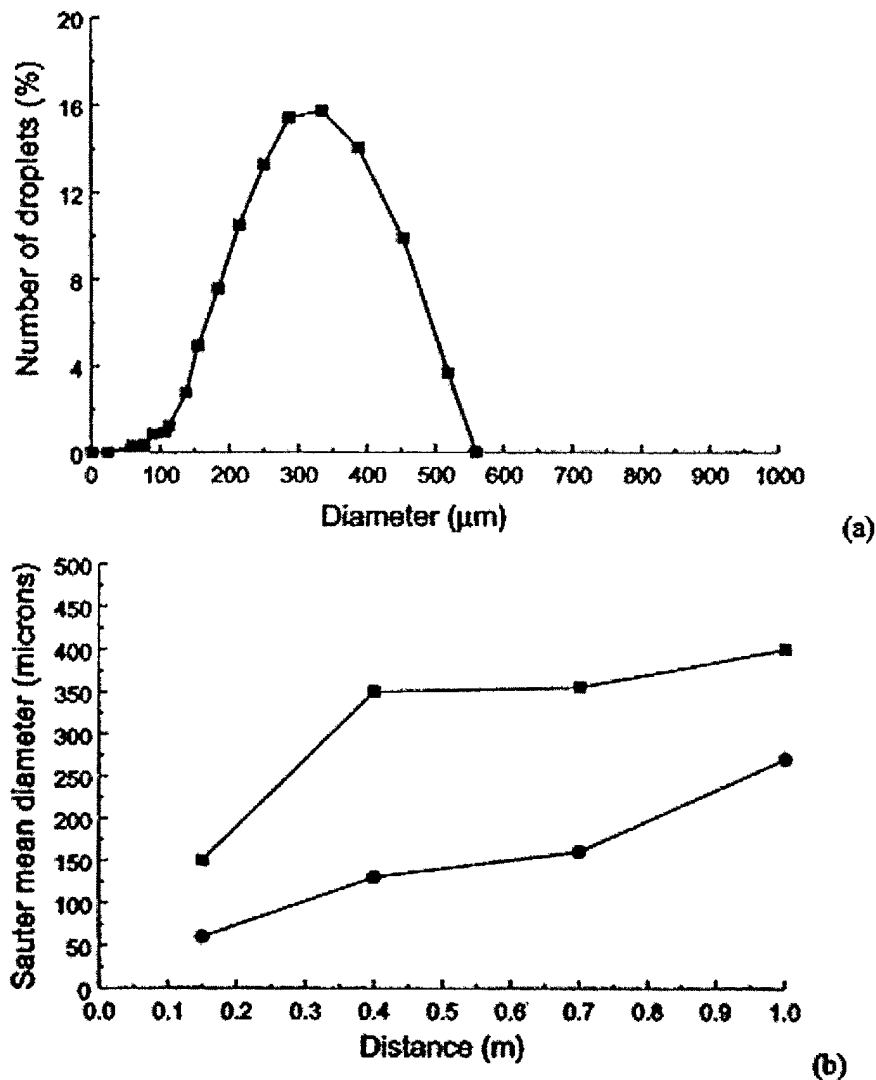


Fig. 8 Droplet size distributions measured using a MALVERN analyzer 1 m below a spray (a), and comparison of the size parameter, D32, obtained with the MALVERN (●) and DANTEC PDA (■) droplet measurement apparatus at various distances below the spray (b).

In a recent work [46], Thomas also provides an explanation for the observation that sometimes even relatively large droplets have been found to be effective in mitigating the effects of explosions. According to him, the answer must lie in the mechanisms of droplet fragmentation and these mechanisms are discussed later in this report. Overall observations from their work are: a) for realistic polydisperse sprays, the major contribution to extinction will come from those droplets with diameters less than 50 microns and therefore there is need to characterize sprays, especially the fraction below 30 microns; and b) an important physical mechanism is the relative acceleration of the droplets compared to the accelerating gas flow.

Norwegian Research on Water Sprays

The work in Norway on explosion mitigation using water has been primarily conducted by the Christian Michelsen Research Institute at Bergen and the Norwegian Institute of Technology at Trondheim. One of the key contributions from this group is a systematic investigation of the flame acceleration effect of water sprays due to the turbulence generated [47]. Experiments were carried out in a 1.5 m³ rectangular box fitted with several nozzle types used in offshore facilities. A burning rate increase of approximately 1.5 to 2 times the nominal flame speeds for propane and 1.4 to 2.3 times the flame speeds for methane were observed in the presence of turbulence generated by the water sprays. Some nozzles generated relatively big droplets (500 to 1000 microns) while fogging nozzles generated sizes on the order of 50-100 microns. The flame speeds in propane-air mixtures for different nozzle types are shown in Fig. 9 as a function of distance. Note that the flame velocities involved are rather low (10-30 m/s). Source of turbulence generation is related to the bulk flow of water and the dimensions of the chamber rather than the dimensions of the droplets. Based on such experiments they conclude that, "water spray causes an increase of explosion loads when the explosions take place in relatively open, low congested environments." (44)

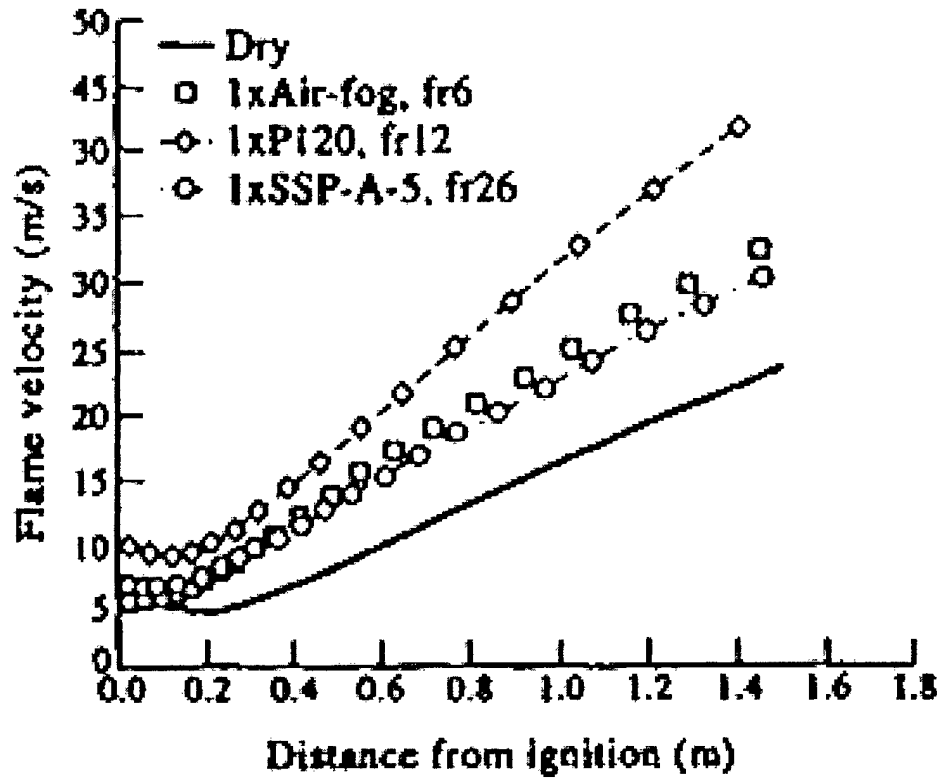


Fig. 9 Flame speeds as a function of distance in propane-air mixtures for four different nozzle types.

They also postulate a mitigating effect due to the evaporation of water droplets in the flame and a consequent reduction in the burning rates. A theoretical study shows that droplets smaller than 10 microns will evaporate in the flame. They acknowledge that the droplets generated by the spray systems used are generally too large to evaporate in the flame. Hence, the droplets must break up to be effective in the flame zone. Strong hydrodynamic forces are needed which could arise due to high flow velocities in vented or unconfined geometries. If confinement is too high, the flow velocities generated may be too low. Van Wingerden [48] states that most effective systems generate droplets that are very small (less than 10 microns) or large (greater than 200 microns). Sizes between 20 and 200 microns are least effective. The reason given is that small droplets evaporate in the flame and large ones will break up. Intermediate droplets (between 20-200 microns) will easily adapt to flow accelerations and as a result will not be exposed to

strong forces to break up. Apart from the size, the amount of water or the water application rate is also found to be important. Also notes that ideally the water spray must be active before ignition has taken place, which can be done in some circumstances by using a combustible gas detection system.

In experiments conducted in a typical offshore module, 28 m x 12 m x 8 m, pressures were reduced by a factor of 20 in some cases [49]. Water curtains were less effective than general area deluge when the same amount of water was introduced because the flame continued to accelerate and they observed a build up of over pressures in between the curtains. Since the work of Acton et al. [36] shows that water curtains are effective on shore, they acknowledge that when larger (less confined) areas are involved, as in on-shore facilities, water curtains may be more effective.

The Norwegian research groups have also developed an explosion prediction tool called FLACS [50, 51]. This is a 3-D CFD based tool allowing for the prediction of the consequences of gas explosions in complex geometries. It is stated to take into account: turbulence generated by water spray systems, droplet acceleration, droplet break-up and reduction of burning rate due to dilution of the gas mixture with water vapor. For this code, the turbulence generation factor (nozzle dependent) is an input and when droplet break-up occurs an immediate effect on the combustion rate is assumed. Also needed are inputs on reduction of turbulent burning velocities dependent on water application rate (nozzle dependent).

They have also addressed one of the negative aspects of the application of water that is often invoked: accidental ignition due to interaction with electrical systems. There have been reports of two explosions [52] caused by ingress of water into electric equipment resulting in sparks. However, Van Wingerden [48] notes that, “use of proper electric equipment and maintenance of this equipment will take away this ignition hazard”. Electrostatic discharge is a second source of ignition. In summary, he states that “an accidental ignition has never occurred” in all experiments performed by Christian Michelsen Research (Norway) and British Gas (UK).

Other Relevant Research on Shock Interactions with Water Sprays and Droplets

There are numerous papers dealing with shock interactions with individual or groups of particles and droplets. In order to make this report concise, only a few key publications that are viewed to have a direct impact on the problem at hand are briefly discussed here.

One of the difficult experimental problems encountered is the visualization of the breakup process when a shock wave interacts with a droplet. Yoshida and Takayama [53] have developed a double-exposure holographic interferometry and applied it to visualize the breakup of a 5.14 mm diameter water droplet when it encounters a Mach 1.56 shock wave in a rectangular shock tube of cross-section, 6 cm x 15 cm. The Weber number corresponding to these conditions is in the thousands. They find that the time variation of the diameter of a breaking droplet measured by conventional optical techniques has been overestimated by up to 35 %. This has implications on the break-up models for large Weber numbers used in computational studies.

Another experimental work that is of relevance is the work of Jones and Nolan [54]. They discuss various means of producing fine sprays as well as measurement techniques used to characterize sprays. They also present various case studies involving water mist suppression of combustion phenomena.

Goosens et al. [55] presented a model for the droplet evaporation process induced by a shock wave propagating in a fog. They show that droplet evaporation times are strongly dependent on the shock strength. However, a linear relationship between droplet radius squared and time is observed during evaporation. The predictions of their model have been verified using experimental data on shocks ranging from Mach 1.2 to 2.1. Their model is, however, expected to be valid only for very small droplets in the range of 1-5 microns, because of assumptions made in the model formulation.

Borisov et al. [56] showed that a thin layer of water on the bottom wall of a tube was enough to quench a detonation in a propane-oxygen-nitrogen mixture under certain conditions. This work is related to the Norwegian research on tube bundles with water [25, 26] that was discussed earlier except that the emphasis here is on the break up of the layer of water into a fine mist due to the high flow velocities behind the leading shock wave. In another work from Russia, Frolov et al [57] showed that water based foams (3-5 kg/m³) could successfully suppress detonations in acetylene and hydrogen. He also stated that the water requirement for suppressing a detonation was less than that required for quenching an ignition behind a shock wave. Surov and Fomin [58] have numerically studied the interaction of a strong shock wave (Mach 11) with a water drop. They find that a characteristic observed in experiments, i.e., the interaction with a strong shock wave results in a spray of fine particles from the drop surface, is very difficult to capture numerically.

4. Methods of Blast Mitigation

In the light of the literature review presented above, it is first informative to briefly discuss the consequences of an explosion in a confined compartment, such as in a ship, and gain a better understanding of the phenomena to be mitigated. If the explosion is due to an incoming missile hit or the combustion of a high-explosive, strong shock waves and even a detonation wave will be generated. Typically, the pressures behind these waves are tens to hundreds of bars and subsequent reflection of these waves could generate even higher over-pressures. Furthermore, such high pressures occur very rapidly, on the order of microseconds and their duration could be a limiting factor. The higher the degree of confinement, the pressures and impulses are likely to be higher. In the case of a missile hit, the opening could present a natural venting that would limit the over pressures generated. Over a longer time, the high temperatures and pressures behind the shock waves could lead to ignition and deflagrative combustion. Even in an empty confined enclosure, a slowly propagating flame can theoretically generate overpressures of up to 8 bars inside the chamber [38]. In practice, different levels of confinement and congestion could generate higher over pressures. In some cases, one of the confining

walls might give way or a vent may open due to the initial blast wave or due to pressure build up, leading to lower overpressures and a vented explosion. Even when the mixture is not confined, large flame accelerations could lead to significant overpressures because the inertia of the surrounding atmosphere creates sufficient restriction. Thus, shock waves (km/s), high-speed deflagrations (10's m/s) and the over pressures generated by these waves (10-100s of bars) are all factors to be mitigated. The time scales of interest could range from microseconds to several minutes. Further studies into the mechanism of explosion development and the time scales involved in specific scenarios of interest for shipboard safety are needed.

There are several options for reducing the hazards from explosion overpressure, including a) strengthening the critical modules, b) venting through suitably designed weakened areas, c) conventional triggered suppressant systems, and d) water based mitigation systems. Option (a) is generally not practicable due to the expenses involved and the difficulties in retrofitting existing ships; b) is not always viable due to physical limitations or level of overpressures generated; (c) is limited to small volumes (limited number of units due to weight penalties and the need for alternatives to halon-1301). The advantages of (d) water based systems are that they may be relatively cheap; effective over large volumes; not "single shot", that is, can be effective over an extended period of time; and can be activated on event detection, potentially inerting the volume to be protected. The potential disadvantages include accidental ignition by a spark following water ingress into electrical fittings and could enhance deflagrations by turbulence generation if not effective early enough. These potential disadvantages are briefly addressed here but further investigations are warranted.

5. Mechanisms of Blast Mitigation

From the review of the literature presented in Section 3 and the discussion of the phenomena to be mitigated for shipboard application in Section 4, the use of water mist is very promising. However, the underlying mechanisms involved in blast mitigation using

water is not so clear and is briefly discussed below before formulating a plan for blast mitigation using water mists.

There are several mechanisms proposed for the effectiveness of bulk water barriers placed around explosives. Keenan and Wager [11] state that a blast wave from the explosion will fragment the water container and transform the water into an aerosol; this aerosol mixes with the hot detonation gases and evaporates. The gases cool and the gas pressure decreases. However, Eriksson and Vretblad [18] note that no afterburning of the detonation products with oxygen will occur because of the lower temperatures encountered. They state that the decrease in the gas temperature will result only in a decrease in the partial pressure of the gas while the additional water vapor could increase the gas pressure. They also do not see a big difference between explosives such as TNT (which is highly oxygen deficient) and other explosives. Therefore, an alternate mechanism proposed is the transformation of the explosion energy into kinetic energy—including the water container materials. In fact, this view of bulk water as a passive barrier that absorbs some of the energy of the explosion is prevalent in many studies. This is not surprising because in many such cases, water barriers are viewed as an alternative to concrete or steel barricades. This mechanistic concept is also reflected in the numerical modeling of such phenomena. For example, Lottero [59], computes the rigid body motion of a water barricade and comes up with a bulk velocity of 173.4 m/s, not concerned about the ability of water sheets to sustain such high velocities without breaking apart. The modeling group at the National University of Singapore also treats the problem as a multi-material issue and emphasizes the need for appropriate equations of state for water [60]. With the limited successes of such studies, others [61] have added an ad-hoc energy transfer mechanism between the explosive products/air and liquid water/vapor to codes to account for some of the observations. However, they [61] do acknowledge that more work is needed to include “additional physics associated with the heat transfer between the materials.”

An alternate mechanism has been proposed by Forsen et al.[62]. They suggest that the expanding gas from an explosion will initiate a shock wave inside the water when it

contacts the closest water surface and cause “spalling” on the opposite side of the volume. This will cause a void inside the water volume that will fill with vapor. Due to the pressure gradient generated, the whole volume will accelerate and be “smeared out”—later broken up into a cloud of water droplets of different sizes. Heat transfer to (and vaporization of) water is of large importance. Breaking up into smaller droplets will result in an increase in surface area and hence lead to faster heat transfer. However, in a companion paper [21], the same group of authors provides a different mechanism. They state that, “past explanations on the mechanism focus on dissipation of detonation energy by changing the water droplets from liquid to vapor state” and provide some analysis to suggest the mechanism is more complex and that evaporation of water droplets is only a small part. Major mitigation is caused by the redistribution of the internal and kinetic energy over the detonation gases, the blast wave and the barrier material.

What can be definitely said is that there is no conclusive mechanistic explanation for the mitigation effects of bulk water barriers and the predominant emphasis has been on the energy transfer mechanisms between the explosion and the bulk water. There are some who view the break up of the bulk water into a fine spray or mist as a precursor. If this occurs then the problem becomes more analogous to that discussed next in the context of water sprays and gas explosions.

The second group of papers discussed was those dealing primarily with mitigating the effects of gas explosions such as in offshore oil platforms and coalmines. Typically, the over pressures encountered in these problems are lower and most of the emphasis is on interaction between deflagrations or incipient ignitions and water sprays. According to Van Wingerden [48] the effect of water spray on gas explosions are two fold. First, activating the spray system causes turbulence in the gas mixture that upon ignition results in an increase of the burning rate. Secondly, it has a mitigation effect. Due to evaporation of water droplets in the flame, burning rates are decreased or it may even be possible to quench the flame associated with the explosion.

Acton et al. [36] discuss the key factors involved in the interaction between the spray and the combustion process. These are, a) expansion ratio of the combustion process (density ratio of the burnt to the unburnt gas), b) rate of production of burnt gas (reaction front). So we need to try to affect these two factors. Maximum reduction in expansion ratio is calculated as 18 % for a 2×10^{-4} water volume fraction of spray (ratio of the volume of water within the spray envelope to the total volume of the spray envelope). Assuming that the overpressure is proportional to the square of the flame speed (and expansion ratio) gives only about a 30 % reduction. This does not account for the observed reductions, which are much larger. Therefore, there must be some quenching of the reaction process. They get an estimate of 30 microns for the diameter of the droplets in order for it to be evaporated completely within the flame front. But the Sauter Mean Diameter for the nozzles used in their experiments is about 900 microns. So there must be some other phenomena such as turbulence or other such aerodynamic processes responsible for reducing the droplet size and making it more effective.

It is such observations that strongly suggest that water sprays with fine droplets, i.e. mists) are needed for effective mitigation. Many studies have focused on conditions that are needed for the generation of such strong hydrodynamic forces. Confined explosions (not involving shocks) are not likely to generate high enough flow velocities and this has been borne out by some experiments. Vented gas explosions or those involving congested environments naturally provide high flow velocities and shear that could break up larger droplets generated by conventional spray systems and increase their effectiveness.

Detonations provide a natural means of generating high transient velocities; hence, it is not surprising that water mists have been found to be particularly effective in suppressing detonations [40]. In this context, it is interesting to note that Lane [63] noted that transient flows could bring about the same mode of break-up at a lower velocity than a steady flow. Most of the classical work of Pilch and Erdman [64] on droplet breakup is for droplets subjected to an instantaneous change in the gas velocity behind a shock wave. Depending on the Weber number, different detailed mechanisms of breakup are

possible, such as vibrational breakup, bag breakup, bag and stamen breakup, sheet stripping, wave crest stripping and catastrophic shattering. In an explosion, the droplets are more likely to experience a flow that accelerates as the explosion evolves [46]. In shock studies [63, 65], a Weber number of 12 is found to define the boundary beyond which fragmentation is observed to occur. Thomas [46] suggests that the critical number of 12 holds for both steady and transient flows. In that paper, he also states, "if a relative velocity between the gas and droplet is such that a Weber number of 12 can be obtained and maintained for a sufficient time then droplet break-up will occur." Wingerden and Linga [66] also confirmed the finding that in both steady and transient flows water droplets broke up when a critical number of 10-12 was reached. The Weber number, We is defined as $We = \rho V^2 d / \sigma$, where σ is the surface tension in N/m, V is the velocity of the gas mixture stream relative to the velocity of the droplet in m/s, ρ is the density in kg/m³ and d is the droplet diameter in m.

Another mechanism by which water-mists can be effective is by inerting a potentially explosive mixture. Sapko et al. [34] showed that in addition to quenching an already established flame, fine water mist can prevent combustion by inerting a gas mixture. The droplets must be fine enough to accomplish this. For methane-air flames, Sapko et al. [34] estimated the critical droplet diameter to be of the order of 18 microns.

6. Key Issues To Be Resolved

As reviewed earlier, the two major areas of past emphasis have been on a) mitigating the effects of condensed-phase explosions by placing water in close proximity, and b) mitigating vapor-cloud explosions either by inerting the mixture, quenching the flames or reducing the deflagration velocities involved. While the knowledge gained from both these classes of studies is invaluable, they do not completely represent the scenarios encountered in shipboard explosions. Therefore, a key issue to be resolved is the effect of geometric (size and complexity of enclosures) and physical (shock strength and potential combustible mixtures, for example) parameters that are relevant to the Navy problem.

Many investigators have stated the need to have very fine droplets. However, significant attenuation has been attained in the past, under certain conditions, with larger droplets. The flow velocities involved and hydrodynamic forces generated are the dominant mechanisms invoked to explain the surprising effectiveness of larger droplets. An issue that needs to be resolved is the mitigation effectiveness of various sizes/classes of droplets. Also needed is a realistic estimate of the level of hydrodynamic forces that are likely to be encountered in scenarios of interest. A key factor is the Weber number involved. To estimate the Weber number we need information of typical flow velocities and droplet sizes involved.

Determining the size effect is not trivial. There are uncertainties in the measurement techniques (as shown in Fig.8) and the effect is not expected to be monotonic. To recall, Van Wingerden [48] suggested that most effective systems used droplets that are very small (less than 10 microns) or large (greater than 200 microns). Sizes between 20 and 200 microns are least effective. The reason given was that small droplets evaporate in the flame and large ones will break up. Intermediate (greater than 20 and less than 200 micron) will easily adapt to flow accelerations and as a result will not be exposed to strong forces to break up. An additional factor that must be taken into account is the fact, that although one talks about mean (Sauter mean or volumetric mean) droplet sizes in a spray, it is unrealistic to expect a single parameter measured at one location to characterize an entire spray. Measurements at a series of locations and the use of expressions that capture the range of drop sizes in a spray will reduce some of the confusion present on the relative effectiveness of different sprays.

The need for area deluge or more specifically the concentration of water mist needed for effective mitigation has not yet been established. There are some studies that suggest that beyond a certain extent, additional water does not provide additional suppression. The amount of water (and its dependence on droplet size) needed for an enclosure of a given volume needs to be determined.

An issue of some concern is the flame acceleration and increase in over pressures observed (see Fig.9) under certain circumstances. However, the flame velocities involved appear to be relatively small and hence the over pressures generated may not be very large for Navy applications. A more careful assessment of this risk would be valuable.

Another issue of some concern is that in many cases when the water mist mitigates the explosions, the smaller over pressure tends to occur earlier (Figs. 6, and 7). This could be of some concern because it could reduce the response times available.

Some of the studies involving blast mitigation with water indicated less positive results in large-scale enclosures [16]. This could be related to the intrinsic complexity of the Alvdalen tunnel system (see Fig. 3) or could be more general. The large and intermediate scale tests by British Gas [36-38] on gas explosions (see Figs. 6, and 7) are more encouraging. However, additional studies on scale-effects will be reassuring.

7. A Plan of Action

To resolve the key issues presented above, a complementary experimental and computational study is needed. There are certain issues that may be best resolved using computational studies. For example, a systematic investigation on the effects of droplet sizes on shock and detonation attenuation. Experimental studies are essential both to validate numerical predictions and to calibrate simplified models used in analytical studies. In addition, the uncertainties involved in the input parameters appropriate for the description of explosives of interest necessitate direct experiments. Experiments at different scales will also be valuable. To some extent, validated numerical models can play a critical role in minimizing the number of experiments that need to be conducted. The effect of geometrical complexities that are characteristic of actual shipboard scenarios is another aspect that can best be predicted using validated numerical models. In fact, to quote Birnbaum et al. [61], "Numerical modeling holds great promise for being able to study the water mitigation problem, not only in the simplified geometries studied, but in more complex situations as well."

8. Summary

Various applications that involve blast mitigation using water have been reviewed in this report. In summary, the ability of water mists to mitigate the effects of blast waves is unquestionable based on the evidence presented above. The unresolved issue is the effective mitigation that can be achieved in specific scenarios such as in a shipboard explosion. This can be resolved only by considering relevant parameters, such as size of the enclosure, geometric complexity of the enclosure, amount of water available, time available to deploy the mist under different scenarios and the size and volume of mist that can be generated cost effectively in a timely manner.

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